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ADAPTIVE PROCESSING FOR LOW RCS TARGETS

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An adaptive system to determine and transmit a radar signal matched to a target's impulse response was designed, breadboarded and tested. The application is to targets which consist of discrete point-like scatterers. A pilot signal consisting of a single short pulse is transmitted. The return from this pilot pulse is range gated in a network which generates a piecewise approximation of the conjugate of the impulse response. This approximation becomes the matched signal which is then transmitted.

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The system was demonstrated to provide nearly theoretical target enhancement even when the pilot pulse return was at the receiver noise level. Operation under situations where the target-impulse response was changing was also demonstrated.

Problem areas in the implementation are described.

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PREFACE

This is the Final Report prepared under the Rome Air Development Center Contract No. F30602-79-C-0142. The program was administered by Mr. Daniel Tauroney, RADC/OCTM.

The Project Manager for this effort was Dr. Steven Weisbrod, the Company's Chief Scientist. Other key personnel involved in this program were Mr. Lee Morgan, Principal Analyst, and Mr. William Hernon, Radar Range Engineer.

1.0 INTRODUCTION

The study described in this report is an extension of the theory developed at Purdue University under Contract F30602-75-C-0082 and experimental work performed by Teledyne Micronetics under Contract F30602-78-C-0163.*

The theory developed by Drs. G. R. Cooper and C. D. McGillem, "Space Time Signal Processing of Radar Returns" shows how the signal from a target can be enhanced over that of a conventional return. This signal enhancement can utilize either frequency or time domain techniques. The previous experimental effort involved a static verification of the time domain approach.

The signal enhancement is achieved by utilizing a transmitter waveform and/or a receiver impulse response that is matched to the target return. As the target aspect angle changes, the relative positions and strengths of scattering centers change. The required transmitter waveform and receiver response also change and the radar must therefore be able to sense these new requirements and adapt to them in real time.

The effort described in this report was primarily devoted to the development, breadboarding, and testing of an adaptive method of generating the transmitting waveform for the time domain approach. A small portion of the effort was devoted to an experimental verification of the frequency domain approach for a complex target.

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* Lee Morgan and Steven Weisbrod, "Advanced Radar Detection and Processing Techniques for Low Electromagnetic Scattering Targets", RADC Final Technical Report, RADC-TR-79-224, September 1979.

2.0 THEORY

2.1 Optimum System

The radar return from a complex target which may be represented by a set of simple isolated scatterers can be enhanced by properly choosing the transmitter waveform and the receiver impulse response.

In the Final Report for the previous study expressions for the optimum transmitted waveform, and receiver impulse response were derived for three cases. The three cases were "matched receiver," "matched transmitter," and "matched transceiver." The criterian for defining optimum was to maximize the signal-to-noise ratio at the receiver output subject to a constant transmitted energy constraint. The discussion considered targets which consist of a finite number of discrete point scatterers with the target impulse response, h, being represented by

$$h(t) = \sum_{1}^{M} a_m \delta(t-\tau_m). \tag{1}$$

The "matched receiver" case is one in which a single short pulse is transmitted and the receiver is designed to maximize the signal-to-noise ratio at the receiver output. In this case the optimum receiver impulse response, k, is given by

$$k(t) = h(T-t) \tag{2}$$

where T is a fixed delay.

The "matched transmitter" is one where the transmitter waveform is chosen to maximize the SNR when the receiver is matched to the reference transmitter pulse (e_o) which is a pulse short enough to resolve the individual scattering centers on the target. For this case, the optimum transmitter waveform is given by

$$e(t) = \sum_{1}^{M} a_m e_o(t-T+\tau_m). \tag{3}$$

The "matched transceiver" is one where the transmitter waveform is optimized subject to the condition that the receiver is matched to the target response to this waveform. In this case a general solution was not found. If, however, the returns from the individual scatterers are spaced by multiples of a constant, τ_o, then any signal of the form

$$e(t) = \Sigma b_n \cos[2n\pi t/\tau_o + \phi_n] \tag{4}$$

is an optimum signal.

A transmit signal consisting of a series of short pulses spaced τ_o apart (some of the pulses may have zero amplitude) is suboptimum but asymptotically approaches the optimum system as the number of pulses in the train increases. The matched transmitter's signal is suboptimum since it is a finite sequence of pulses but is within a few dB of optimum if the scattering centers are equally spaced.

The adaptive transmitter investigated in this study generates an approximation to the matched transmitter signal. The receiver used was fixed so that we are considering approximations to the optimum signal for the actual situation but the signal would be suboptimum if the receiver were also made adaptive.

2.2 Adaptive Matched Transmitter

When the transmitted signal is constrained to be an RF signal modulated by a sequence of pulses, the optimum waveform is one in which the pulse sequence is the time image of that pulse sequence received when only a single pulse is transmitted. The relative phases of the RF within each transmitted pulse are the negative of the relative phases of the RF within each pulse in response to a single transmitted pulse. In other words, the transmitted signal should be the time image of the signal received in response to a single transmitted pulse.

Figure 1 is a block diagram of a system which could generate this signal and adaptively change in response to target changes. Its operation will be explained by reference to Figure 2 which shows waveforms at various places within the system when the target consists of 3 distinct scattering centers. The first center has a smaller amplitude than the other two and the third center causes a phase reversal as compared with the first two.

The target response is sampled by transmitting a single pilot pulse of RF (the signal U(t) in Figure 1 and waveform a in Figure 2). The return from the target when this pilot pulse is transmitted is shown as waveform b in Figure 2 and is denoted by $D_1(t)$ in Figure 1 where it is shown being input to the first tapped delay line. This delay line has equally spaced taps with the tap spacing being less than one-half wavelength at the RF frequency. At some time, t_o, when the target return is entirely contained in the first delay line the voltages present at the taps are gated into the second delay line through switches which are controlled by an impulse generator. Figure 2c shows the voltages as they appear at the outputs of the switches at time

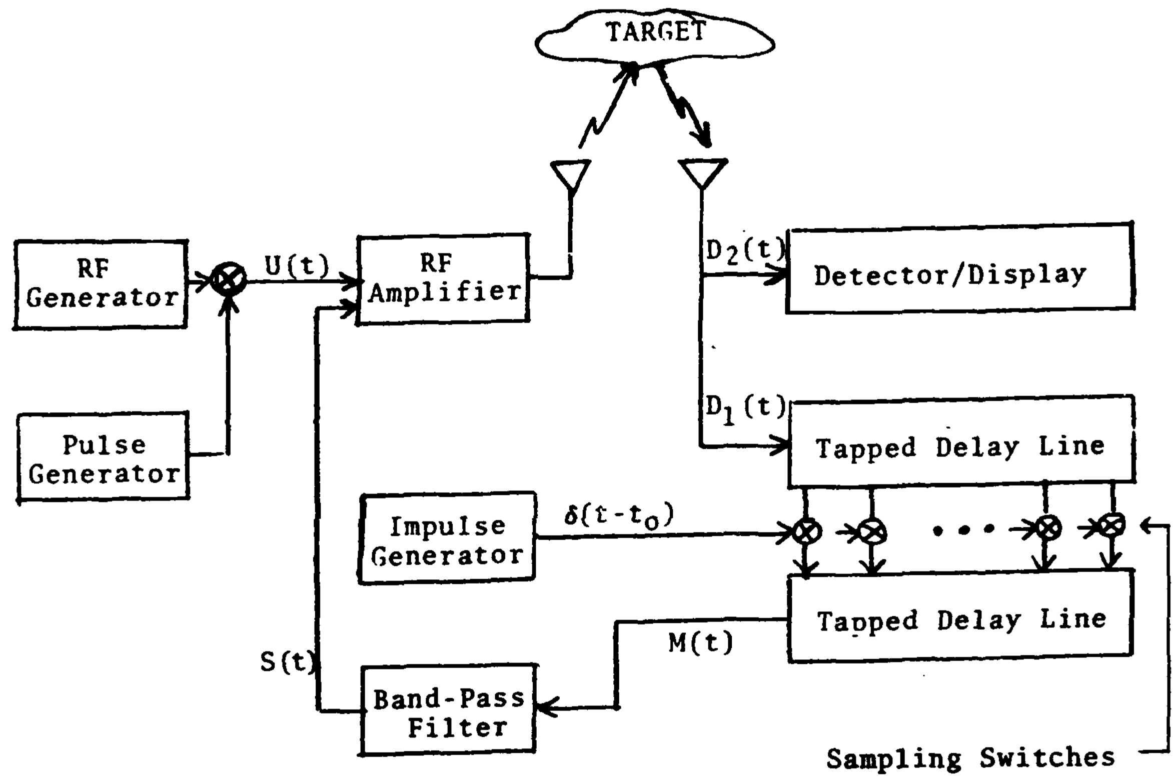


FIGURE 1 IDEALIZED ADAPTIVE MATCHED SIGNAL SYSTEM

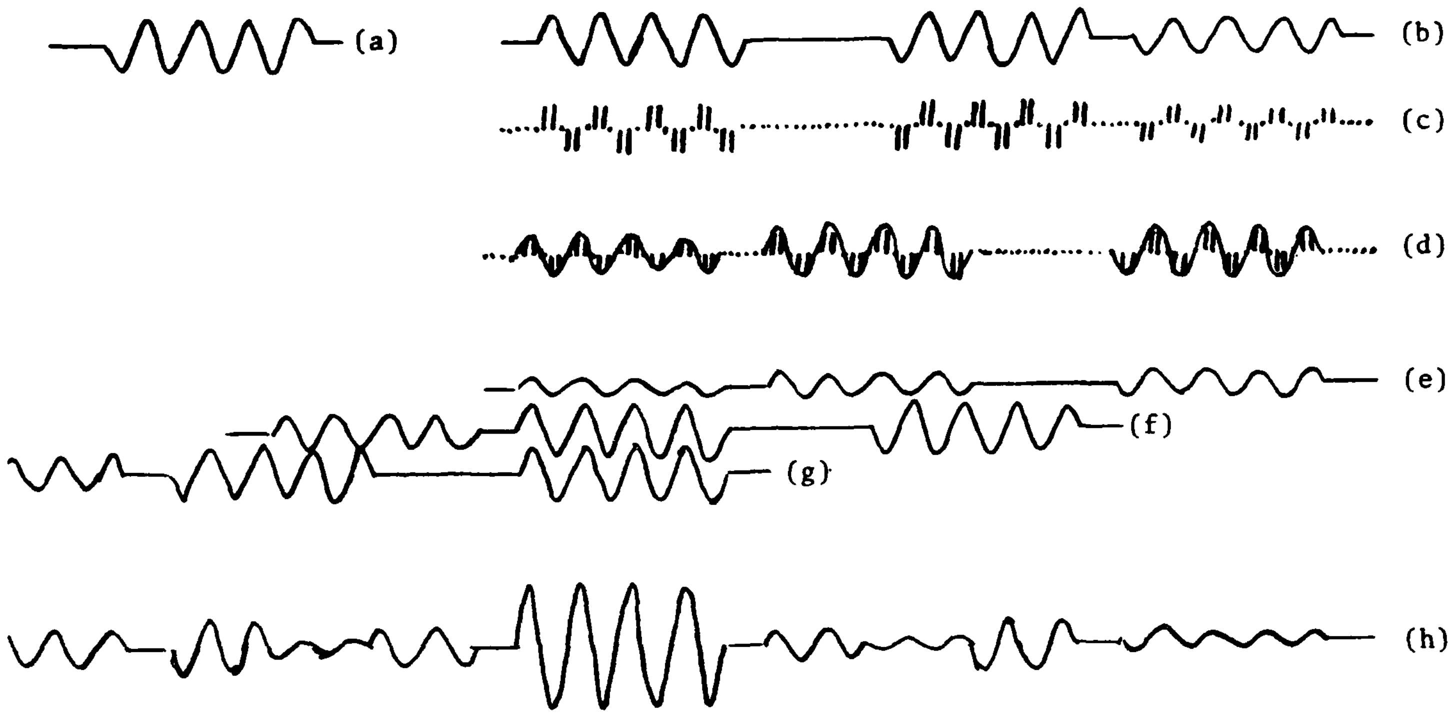


FIGURE 2 WAVEFORMS WITHIN MATCHED FILTER SYSTEM

a) Pilot Pulse Transmitted Waveform; $U(t)$
b) Target Response to Waveform a; $D_1(t)$
c) Sampling Switch Outputs at time t_o
d) Bandpass Filter Input (impulses) and Output (envelope)
e,f,g) Target Response to Three Pulses of Waveform d
h) Target Response to Matched Waveform d; $D_2(t)$

t_0. The output from the second delay line is sent through a bandpass filter centered at the RF frequency. The input and output waveforms at this filter are shown in Figure 2d. Notice that the last input to the first delay line is the first output from the second delay line. The output of the bandpass filter is therefore a time-reversed replica of the signal D(t). This signal is now amplified and retransmitted. The return from the target is now denoted by $D_2(t)$ and is gated to the detector display section of the radar as shown in Figure 1. This signal is also shown in Figure 2h and is the sum of the three signals shown in Figures 2e, f, and g.

This system is in principle capable of both determining and tracking the optimum waveform. Theoretically this system will realize the benefits of the matched transmitter approach even if the signal-to-noise ratio in the bandpass filter output is less than unity since the noise component of this signal will be uncorrelated with the target response function. There is, however, a price to be paid for this capability. A fraction of the available energy must be used to transmit the pilot signal U. Another fraction of the available energy will be wasted in transmitting noise that appears at the output of the bandpass filter.

The relative amount of energy transmitted as noise will clearly depend upon the signal-to-noise ratio of the response to the single pilot pulse which in turn will be determined by how much energy is put into this pilot pulse. Thus, increasing the fraction of available energy contained in the pilot pulse will decrease the fraction of energy wasted in transmitting noise. There will, therefore, be an optimum ratio of pilot power to matched signal power which will maximize the SNR of the response to the matched signal.

While the system shown in Figure 1 would theoretically serve as an adaptive matched signal system it is not practical due to the requirements for delta function sampling and the large number of channels involved (greater than four times the size of the target measured in RF wavelengths). In this program a suboptimum implementation was used.

The actual system investigated experimentally is shown in Figure 3 with details being shown in Figures 4 and 5. The concept is similar to that shown in Figure 1 but there are some significant differences. First, the sampling of the received signal due to the pilot pulse utilizes finite width windows rather than delta functions and the sampling pulses were approximately Gaussian shaped rather than rectangular. Secondly, the time interval between samples is approximately equal to the window width rather than one-half the RF period. Thirdly, the "tapped delay line" was implemented by a combination of power dividers and combiners.

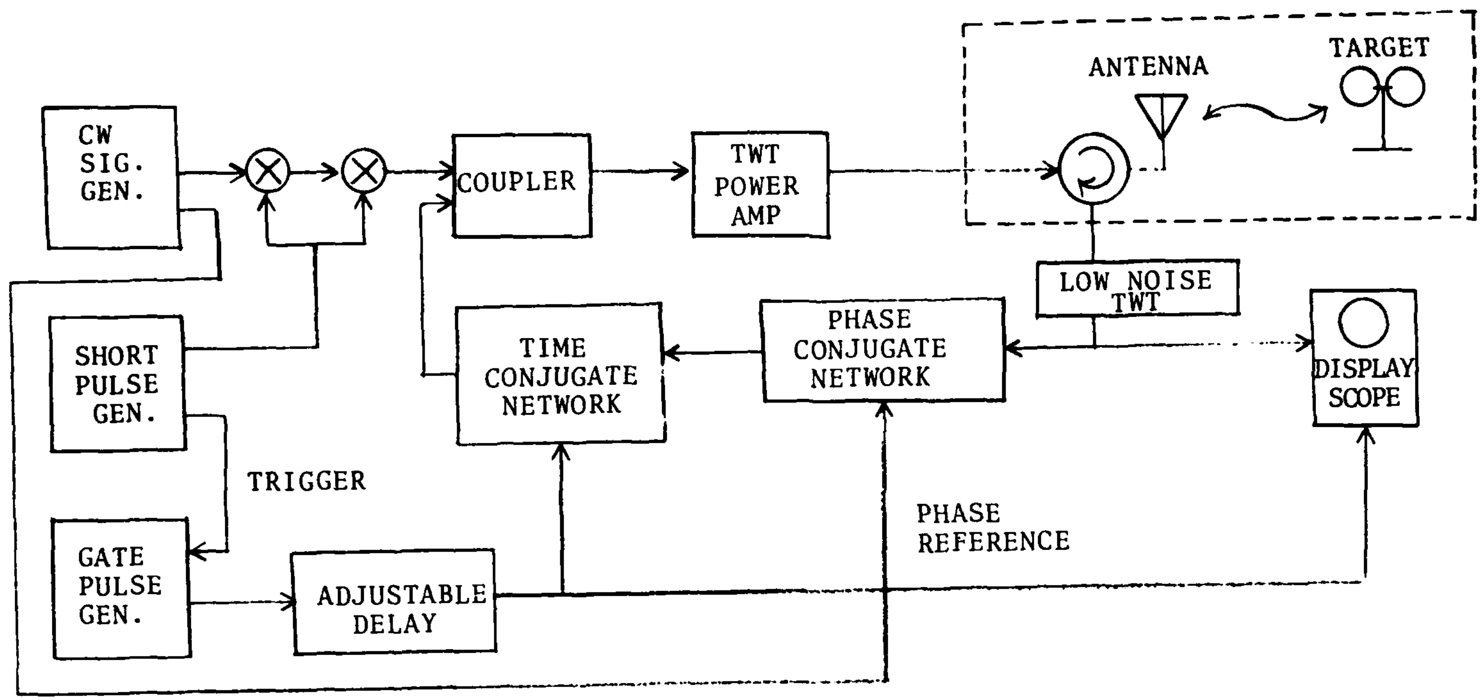


FIGURE 3 ADAPTIVE MATCHED TRANSMITTER SYSTEM

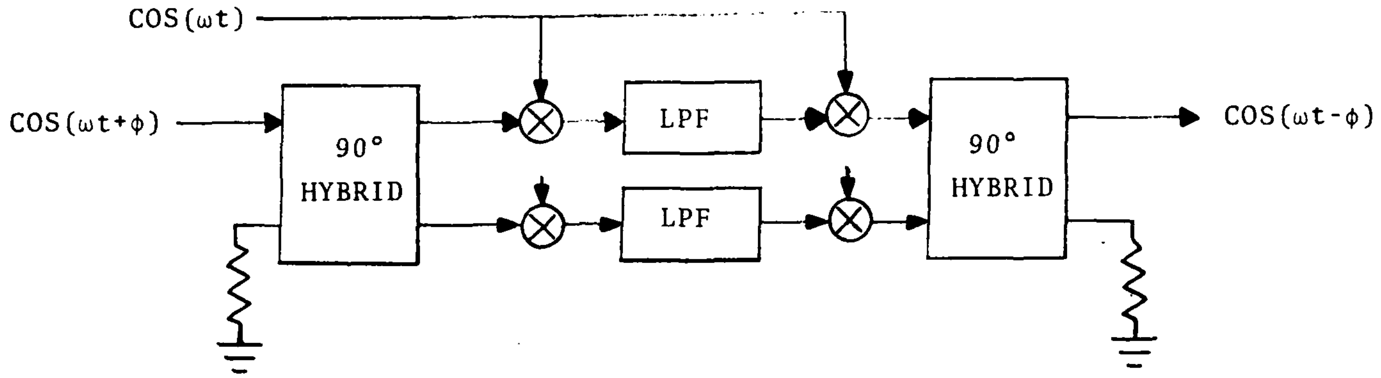


FIGURE 4   PHASE CONJUGATE NETWORK

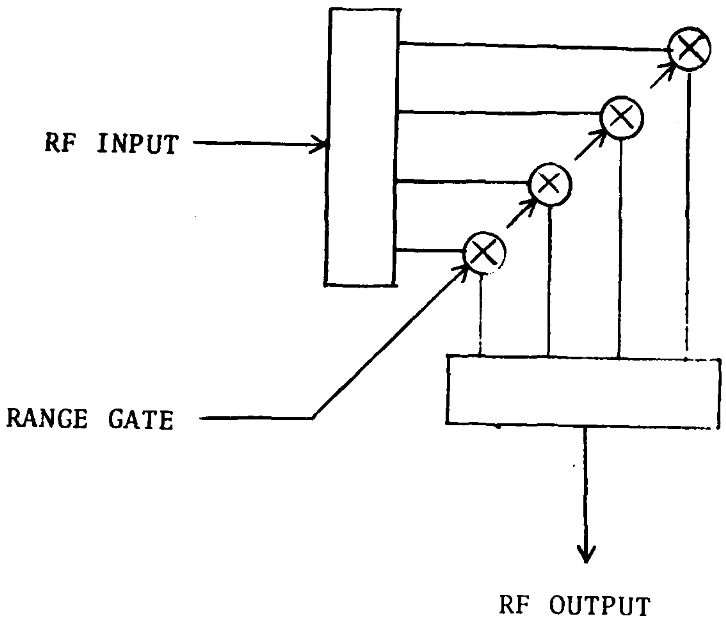


FIGURE 5 TIME CONJUGATE NETWORK

2.3 Effects of Finite Sampling Width/Spacing

The theory calls for sampling at very closely spaced intervals with impulses. Ideally, the sampling should be at least twice per RF cycle. Such sampling was not possible during these tests so that an approximation scheme had to be developed. This approximation consisted of sampling with finite width gates at intervals equal to the gate width. The sampling interval was made a submultiple of the short pulse width.

When this sort of sampling is used there are two effects which limit the degree to which the desired adaptive signal is implemented.

The first effect is that phase now becomes a factor. The theoretical adapted signal is the time image of the target impulse response. This implies that not only must the envelope be time reversed, but the RF phase must also be conjugated. To make this explicit consider the transmitted pilot pulse to be

$$p(t) = A(t)\cos(\omega t) \tag{5}$$

where A(t) is the short pulse envelope function. When the target consists of a number (N) of resolvable point scatterers the target response is

$$s(t) = \sum_{1}^{N} a_i A(t-\tau_i)\cos(\omega t-\phi_i). \tag{6}$$

The adapted signal is ideally the time reversed response or

$$e(t) = s(T-t) = \sum_{1}^{N} a_i A(T+\tau_i-t)\cos(\omega t-\omega T+\phi_i). \tag{7}$$

which has a time imaged envelope and the relative pulses of the components are conjugated.

The second effect of finite pulse sampling in the time conjugated network is a deviation of the envelope from the idealized shape. This deviation is a function of the number of samples per pilot pulse width and the separation between scatter components. The return when the adapted signal is transmitted will be fully enhanced for a period of time that is usually less than the basic pulse width. In fact, if the time conjugate network has N taps per pulse length the time enhanced measured in pulse widths will vary between (1-1/N) and 1. A receiver system that is matched to the basic pulse will produce a peak response that is in the same ratio to the ideal peak as the enhanced time is to the pulse width. The minimum enhancement will occur when the spacing between two targets is an odd multiple of one-half the tap spacing and the maximum enhancement will occur when the target spacing is an integral multiple of the tap spacing.

These effects are best illustrated by graphically constructing the response for a number of representative cases. Figures 6 through 8 show the responses for minimum enhancement situations with 1, 2 and 4 samples/pulse. These figures are similar so only the first will be discussed in detail. The signal on line a is the pilot pulse return on delay line 1 from a two scatterer target at the beginning of the sampling gate. On line b is the signal on delay line 2 at the end of the sampling gate. This is also how the return of the "adapted" signal from the first scatter will look. On line c is shown the adapted signal return from the second scatterer and line d shows the total return. The part of the signals that result from the pilot pulse returns due to the closest scatterer is shaded. In this case, the adapted signal returns from the two scatterers overlap in time only in a region which is a result of the pilot pulse reflectors from the first scatterer as shown by the shading of both components. When this situation occurs, the phases of the overlapping signals do not have a defined relationship so that the composite envelope is shown as dotted in this region. Figure 7 shows the results for sampling twice per pulse. In this figure there is a true enhanced region which lasts for one-half pulse length. Finally, Figure 8 shows the results when the pilot return is sampled four times per pulse. The enhanced region here is three-fourths of the pulse length and further improvement will be slow.

Figures 7 and 9 illustrate the effects of scatterer spacing for two targets for sampling at twice per pulse.

The signal envelopes shown in these figures are of course idealized, but the main features will be recognized in the data photographs shown in Figures 19 - 21.

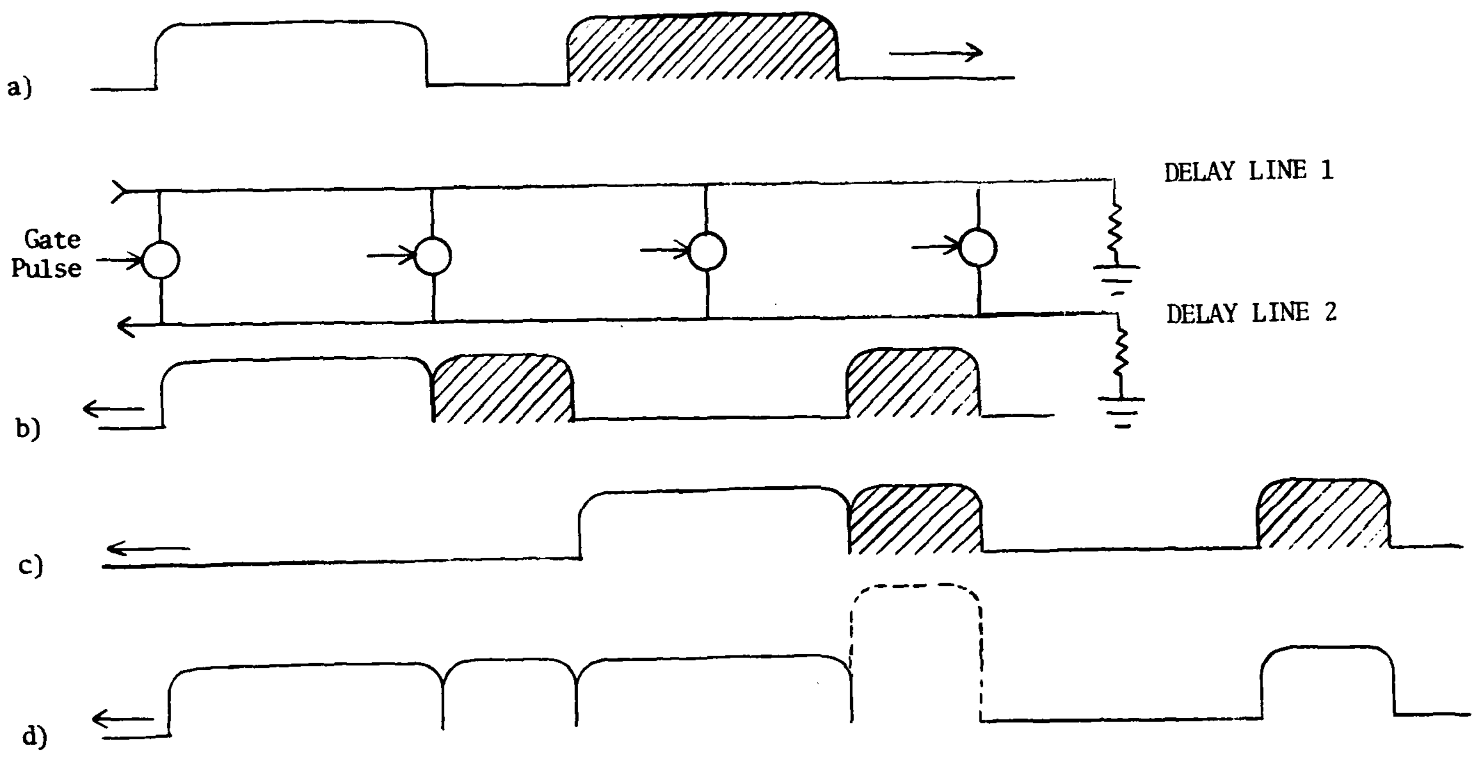


FIGURE 6 GRAPHICAL CONSTRUCTION OF ADAPTED RESPONSE FOR TWO TARGETS AND SAMPLING ONCE PER PULSE.

a) Signal on Delay Line 1 at Start of Sampling Gate.
b) Signal on Delay Line 2 at End of Sampling Gate and Return From First Target.
c) Return From Second Target.
d) Total Return.

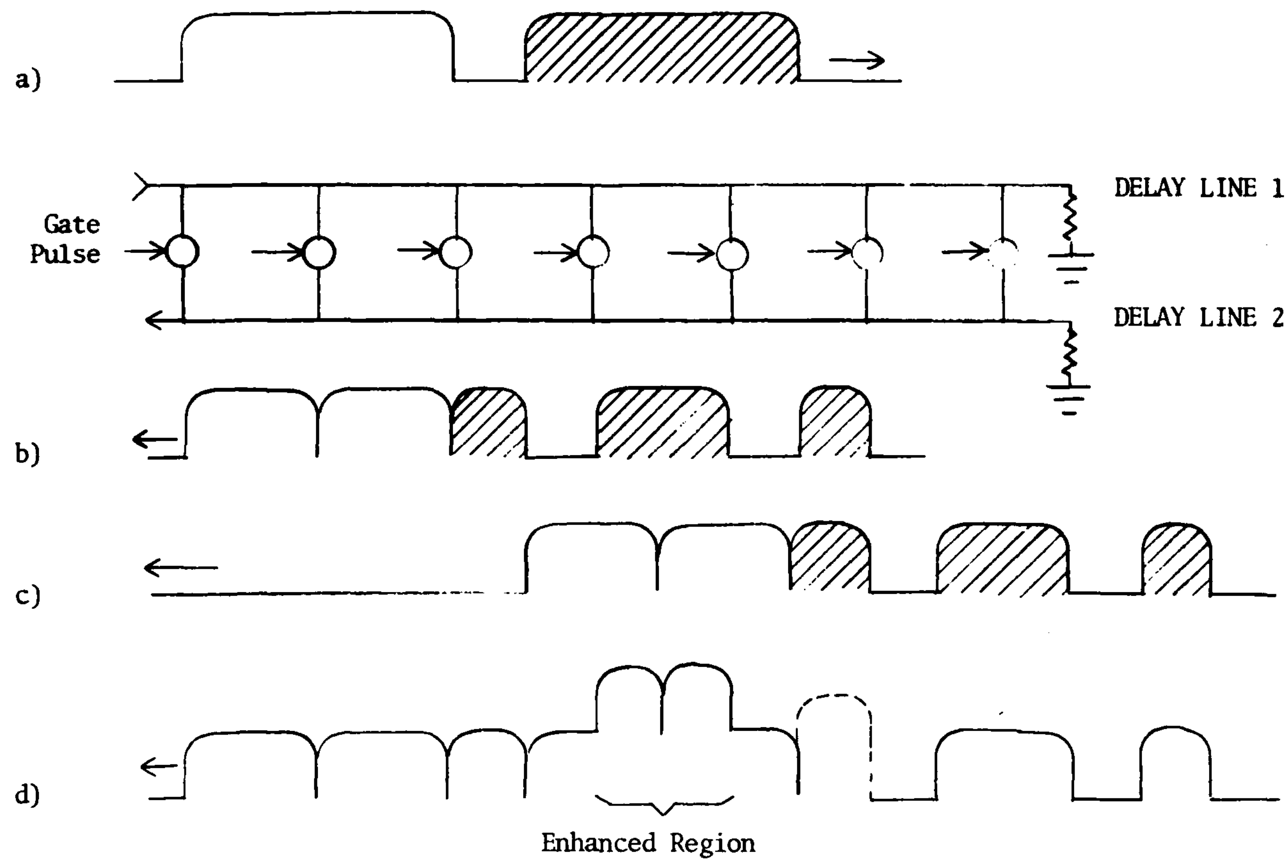


FIGURE 7 GRAPHICAL CONSTRUCTION OF ADAPTED RESPONSE FOR TWO TARGETS AND SAMPLING TWO TIMES PER PULSE. DELAY = 0.25 PULSE WIDTH.

a) Signal on Delay Line 1 at Start of Sampling Gate.
b) Signal on Delay Line 2 at End of Sampling Gate and Return From First Target.
c) Return from Second Target.
d) Total Return.

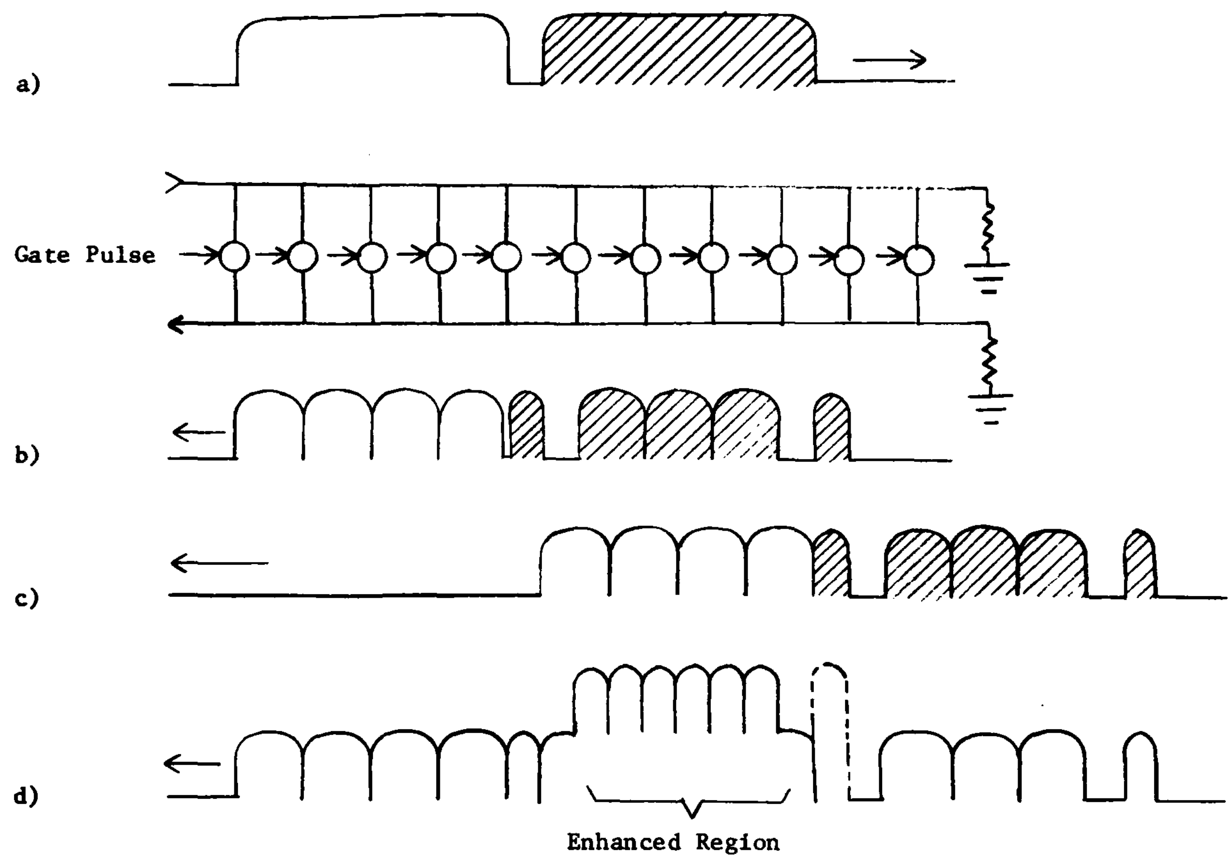


FIGURE 8 GRAPHIC CONSTRUCTION OF ADAPTED RESPONSE FOR TWO TARGETS AND SAMPLING FOUR TIMES PER PULSE. DELAY = 0.125 PULSE WIDTH.

a) Signal on Delay Line 1 at Start of Sampling Gate.
b) Signal on Delay Line 2 at End of Sampling Gate and Return From First Target.
c) Return From Second Target
d) Total Return.

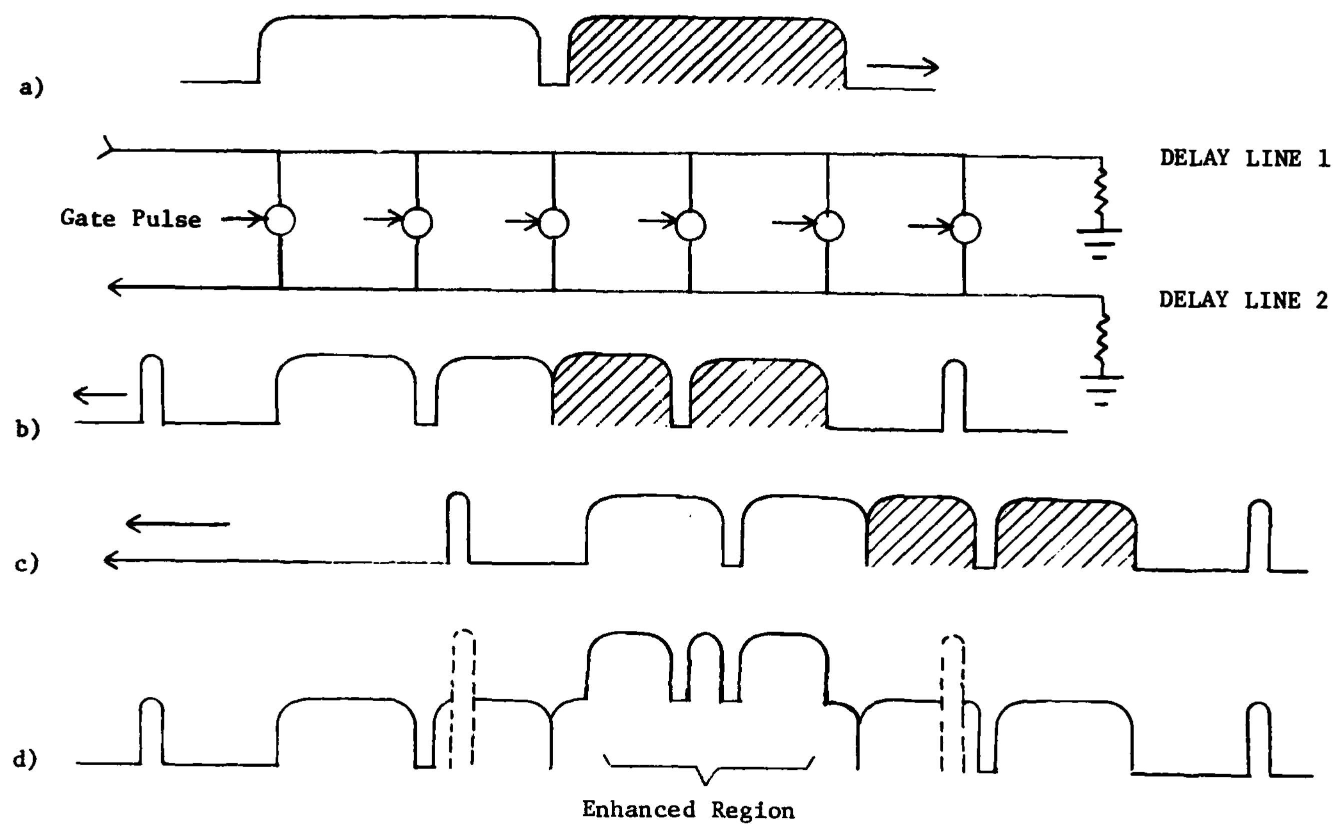


FIGURE 9 GRAPHIC CONSTRUCTION OF ADAPTED RESPONSE FOR TWO TARGETS AND SAMPLING TWO TIMES PER PULSE. DELAY = 0.125 PULSE WIDTH.

a) Signal on Delay Line 1 at Start of Sampling Gate.
b) Signal on Delay Line 2 at End of Sampling Gate and Return From Second Target.
c) Return From Second Target.
d) Total Return.

3.0 ADAPTIVE MATCHED IMPULSE RESPONSE

3.1 Experimental Setup

The basic system utilized in the experiments is block diagrammed in Figures 3, 4, 5, and 10.

Referring to Figure 3, the pilot pulse is generated by pulse modulating a 6 GHz signal, amplifying in a medium power (10 watts peak) TWT and transmitting. The return from the target is coupled to a low noise receiving TWT via a circulator. The output of the receiving TWT is sent directly to a sampling oscilloscope for viewing and to the adaptive transmitter network where the matched transmitter signal is formed. The adaptive transmitter network consists of two parts, a phase conjugate network diagrammed in Figure 4 and a time conjugate network shown in Figure 5. The adapted waveform is coupled back to the transmitter TWT where it is amplified and transmitted. The amplified return from the adapted transmitter signal is viewed on the sampling oscilloscope.

Most of the tests were performed using a simulated propagation path-target combination instead of the real combination indicated inside the dotted box in Figure 3. The simulation network is diagrammed in Figure 10. By simulating the target it was possible to study in a controlled fashion the effects of such factors as the number, relative amplitude, relative phase, and relative delay of the scattering centers. It was also possible to insert extra noise into the receiver front end, thus varying the receiver SNR without changing the levels present in the adaptive network.

The phase conjugate network, Figure 4, operates in the following fashion. The input signal is

$$A(t)\cos(\omega_o t+\phi)$$

where the phase reference is the locally generated cw signal. This is split into two parts, one of which has a phase lag of 90 degrees. After mixing with the reference signal the two parts are passed through low pass filters the outputs of which are

$$A(t)\cos\phi$$

and $$A(t)\cos(\phi-90°) = A(t)\sin\phi.$$

These are then used to modulate the reference signal and recombined again with a 90-degree phase lag in the same part that was initially phase shifted. The recombined signal then is

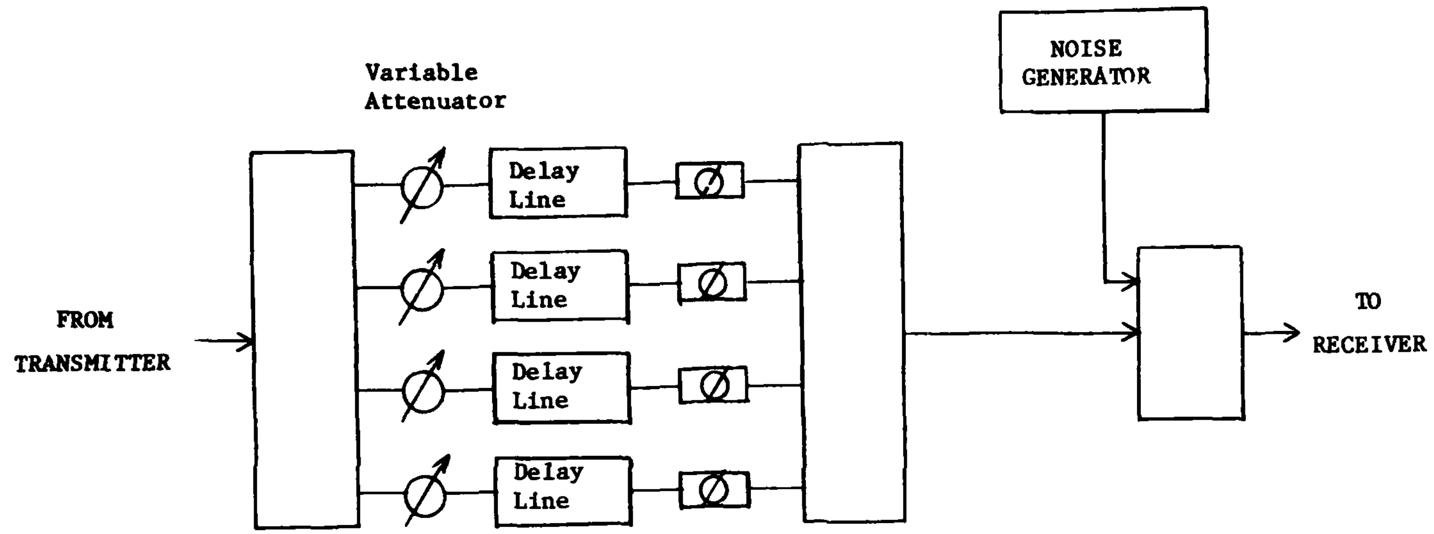


FIGURE 10 TARGET SIMULATION NETWORK

$$A(t)\cos\phi\cos\omega_o t + A(t)\sin\phi\cos(\omega_o t - 90°)$$

which simplifies to

$$A(t)\cos(\omega_o t - \phi).$$

The network thus performs a true conjugation of the phase of any input signal which has a spectrum width about the reference frequency that is less than the bandwidth of the low pass filters. In our measurements the low pass filters had a bandwidth of 2 GHz. Clearly, there are alternate implementations which will accomplish the same objective. One of these would be to replace the quadrature hybrids in the signal paths with power splitters and split the reference signal into in-phase and quadrature components.

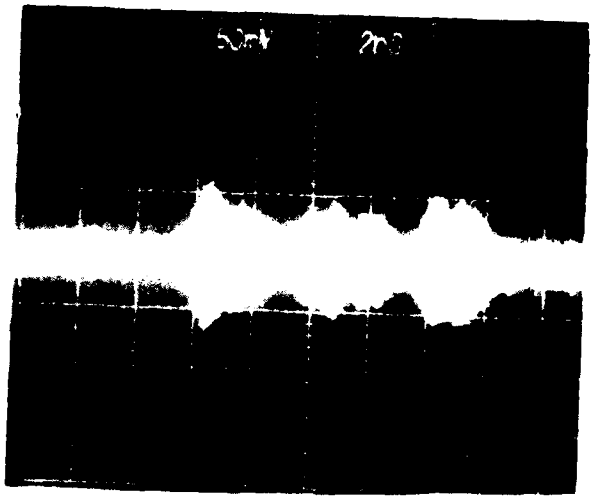
The time conjugate network, Figure 5, physically consists of an N-way power splitter, a set of N-fixed delay lines, a mixer in each line, another set of N-fixed delay lines, and an N-way combiner. The first set of delay lines differ progressively by a constant delay increment τ_o and the second set is identical with the first. The mixers serve as gates and pass signals through when a gate pulse is present on the other mixer input. The gate pulses to the mixers are simultaneous and are supplied from a short pulse generator which is synchronized with the transmit pulse and delayed a variable amount. In effect, the gate pulse serves as a range gate for the adaptive system. The mixers actually serve as multipliers with their outputs being the product of the two inputs. Ideally, the gate pulses should be rectangular of width τ_o and the mixers should allow no signal to pass when the gate pulse is absent. In practice, the gate pulses are more nearly Gaussian in shape and the isolation of the mixers was between 20 and 25 dB at the test frequency of 6 GHz. During most of the tests the number of taps (N) was 4 and the tap spacing (τ_o) was 2 nsec.

3.2 Simulation Tests

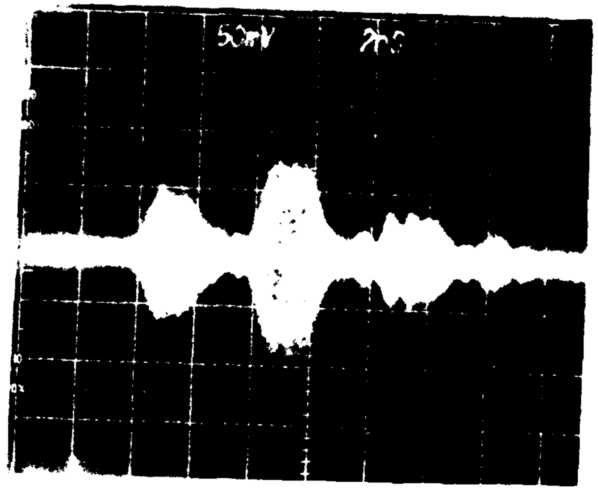
The tests using a simulated propagation path-target were used to define the critical problems in implementing the adaptive technique originally proposed. As a result of these tests two major modifications in the technique were found to be required and several lesser problem areas defined.

The first modification that was determined to be necessary was the inclusion of a method for conjugating the phase of the received signal prior to retransmission. Figure 11 shows what happens when this network is omitted and the target consists of two scatterers. When the relative delays of the returns from the two scatterers differ by an integral multiple of half

NON-CONJUGATED PHASE - TWO COMPONENTS



CANCELLATION
(a)



ADDITION
(b)

FIGURE 11 ADAPTIVE SYSTEM OUTPUT WITHOUT PHASE CONJUGATION wavelengths the system behaves as designed and signal enhancement occurs as shown in Figure 11b. When the relative delays differ by an odd multiple of quarter wavelengths the adapted returns from the two targets cancel as shown in Figure 11a. Inclusion of the phase conjugate network eliminates this effect as illustrated in Figure 12 which shows the return from the adapted transmitter signal as the relative phases of the two scatterers are changed. Although the inclusion of the phase conjugate network eliminates the dependence of the peak return on scatterer phases, the received pulse train still is a function of this parameter. This is illustrated in Figure 13 which shows the adapted return from a three-scatterer target for all targets in phase (a) and with the middle target delay shifted one-quarter wavelength (b). The peak enhancement is clearly unchanged but the two-time sidelobes on either side of the peak change from enhanced to cancelled as the relative delay changes by this amount.

The second modification that was found to be necessary was the requirement that the delay line taps and sampling gate widths in the time conjugate network have to be less than one-half the pilot pulse width. The fundamental reasons for this are discussed fully in Section 2.3. This requirement can be relaxed only if the relative delays between scattering centers are integral multiples of the tap spacing. For many of the results presented in this section this condition was satisfied and the taps' spacing was set equal to the pilot pulse width.

A lesser problem but one which must be carefully considered, is that the tap spacings must be integral multiples of the carrier frequency wavelength. Failure to insure this condition will have the same effect as an unconjugated phase shift between scattering returns.

Another problem that must be addressed in the system design is the general one of trying to obtain the idealized sampling gate response. There are at least two problem areas here. The first is obtaining extremely fast gates with high on-off ratios across the signal bandwidth. The gates used in these measurements do not really satisfy this requirement with typical on-off ratios of 20-25 dB. This has two implications. First, without further precautions a significant fraction of the available average transmitted power could be wasted in transmitting signals that are adapted for targets that are not in the desired range gate. This can be simply solved by gating the output of the time conjugate network with a range gate whose width is comparable to the expected target lengths. The second implication of a finite on-off sampling gate ratio is the possibility of substantial errors in the adapted signal due to leakage through the gates when they are in the "off" state. This results in imperfect time conjugation of the target impulse response and consequent changes in target enhancement. When the on-off ratio is 20 dB there is a possibility for a 1 dB reduction

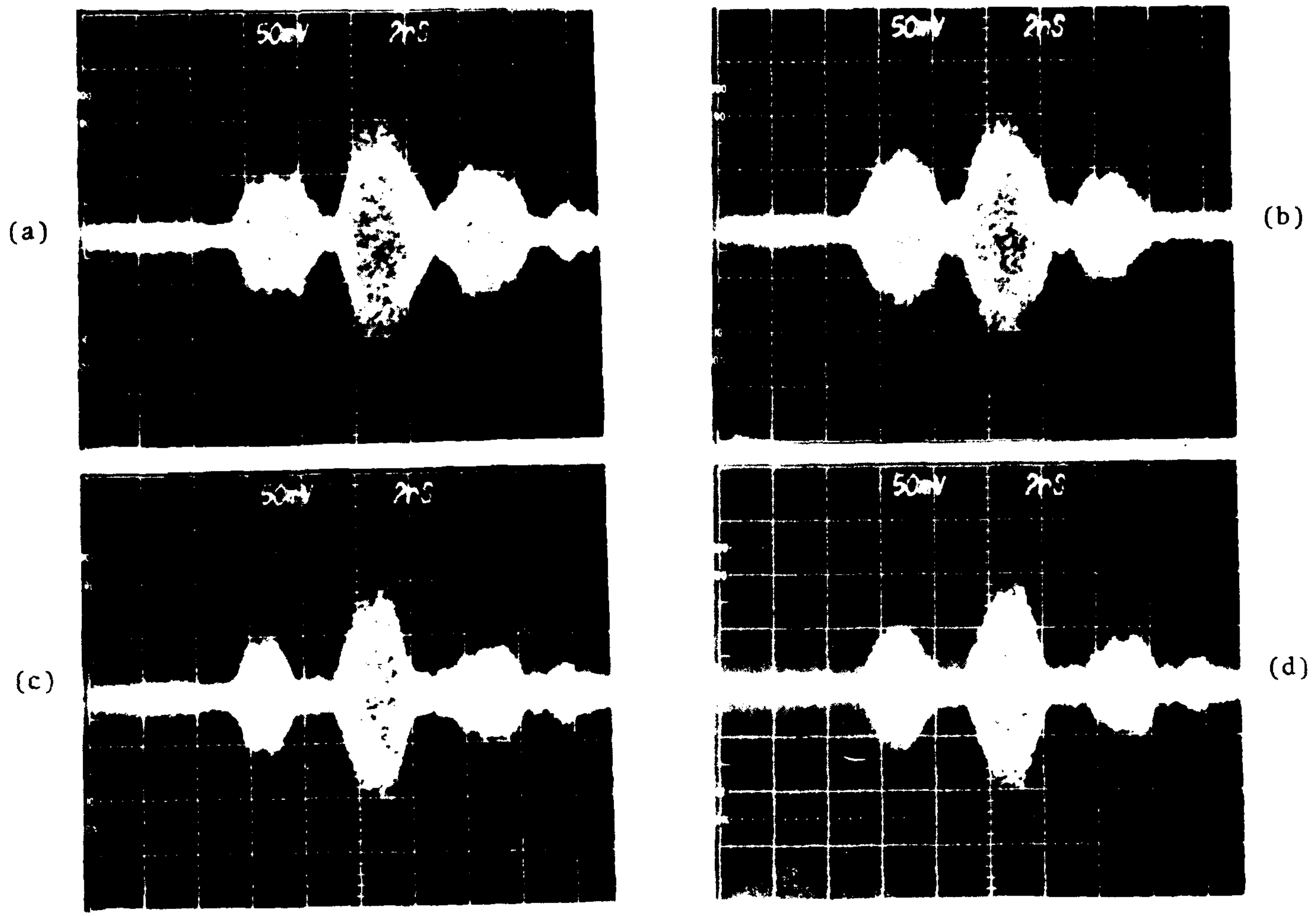
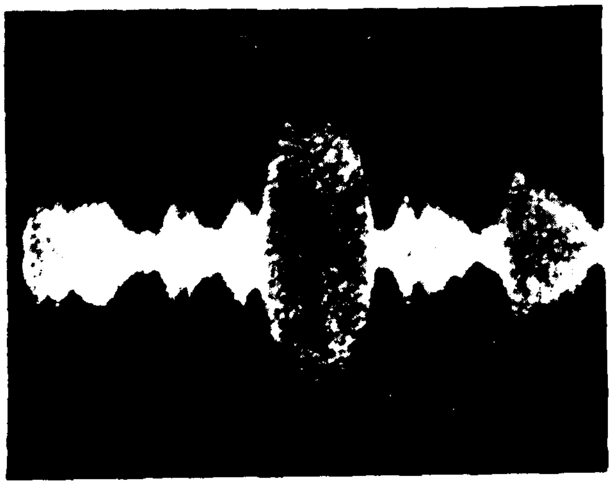


FIGURE 12 ADAPTIVE SYSTEM OUTPUT - TWO COMPONENTS WITH VARIOUS RELATIVE PHASES
a) 160° b) 0° c) 125° d) 80°

(a)



(b)

FIGURE 13 ADAPTIVE SYSTEM OUTPUT - THREE COMPONENTS WITH VARIOUS RELATIVE PHASES

a) All in Phase

b) Component Two Out of Phase

in the enhancement.

The second problem area associated with trying to obtain the idealized sampling gate response is the one of turning the gates on and off fast enough. The mixers used as gates in these experiments had sufficient frequency response to function for this purpose. The gate pulse, however, did not have an adequately fast rise and fall when it arrived at the gates. This is partly due to difficulties in generating the pulse originally and partly due to bandwidth limitations in the network used to transfer the single pulse to the several gates. These problems are accentuated by the requirement that the sampling pulse be less than half as wide as the pilot radar pulse. Figures 14 and 15 illustrate the problems we are discussing. Figure 14 is an example of the gate pulse as it appears at the mixer input. There are two possibilities with this sort of nonrectangular pulse. One can make the 3 dB pulse width equal to the tap spacing. When this is done, significant leakage through adjacent taps occurs as shown in Figure 15. This figure shows the time conjugate network output when the input is a single pulse whose width is equal to the tap spacing and the total gate pulse width is somewhat wider than the tap spacing. The leakage through the adjacent gates due to early turn-on and late turn-off are clearly shown. Alternatively, the gate pulse can be narrowed so that its 20 dB width is equal to the tap spacing. When this is done, the output of the time conjugate network becomes a train of pulses each shaped like the gate pulse. For example, if the network input is a single pulse whose width is twice the tap spacing the output will be a pair of essentially nonoverlapping pulses. In a real system, the narrow gate pulse approach would be preferred and suitable bandpass filters would be added to smooth the response. In most of the measurements, narrow gate pulses were used but the appropriate filters were not available so that the network outputs maintained the split pulse appearance. A good example of this is shown in Figure 19.

Some examples of the final system output for simulated targets with two and three scattering centers have already been shown in Figures 12 and 13. Figure 16 is another example for a three-scatterer target. To be noted here is the difference between the early time (on the left) and late time behavior. This is a typical result and is due to such things as gate leakage and reflections from mismatches in the system.

There were some other problems encountered in the breadboarding of the system which point to areas that will need to be considered in actual hardware development. First, this is a short pulse system and therefore requires that all internal interfaces be well matched to avoid reflections. This is a relatively serious problem in a breadboard system due to the fact that elements are interfaced with cables. In a production system the problem should be less since the components would be integrated into a stripline type of structure. Second, the

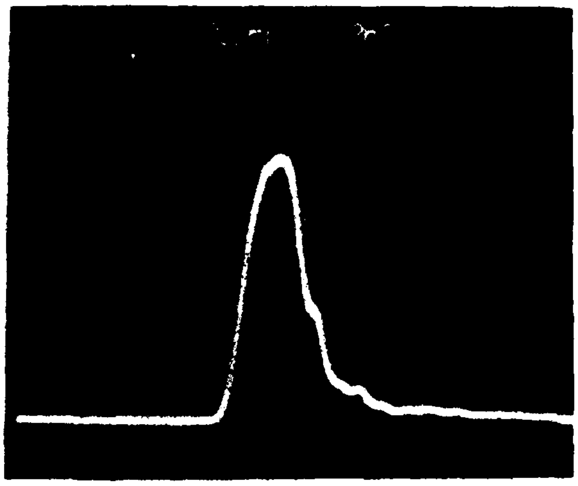


FIGURE 14 TYPICAL SAMPLING GATE PULSE

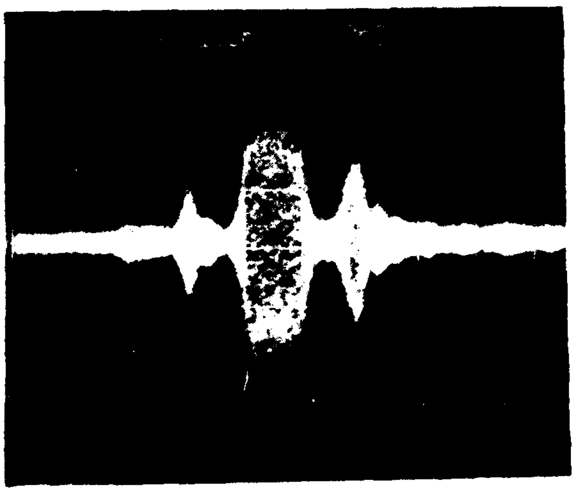


FIGURE 15 TIME CONJUGATE NETWORK OUTPUT.
ONE INPUT PULSE.

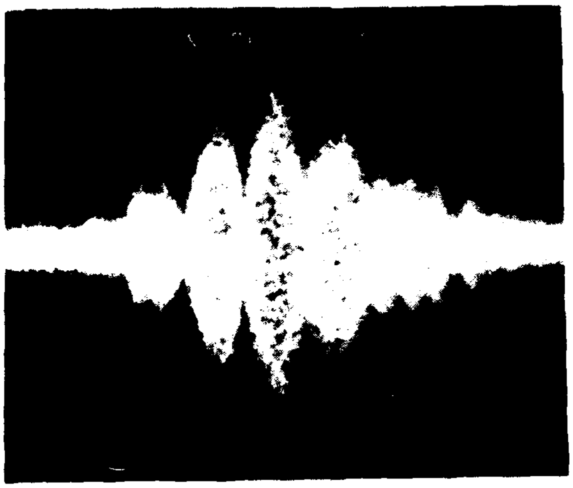


FIGURE 16 THREE SCATTERER SIMULATION

implementation used for the phase conjugate network permitted significant leakage of the reference signal into the remainder of the system. This was solved by introducing a cancellation signal. Third, there was some difficulty in obtaining the proper signal levels at various points in the system. Basically, this was solved by placing amplifiers between the various elements of the system (i.e., between the phase conjugate network and the time conjugate network). Finally, there was a tendency for the system as a whole to oscillate at a frequency where the gates had a very poor on-off ratio. This is inherently a system which has feedback and so oscillations are always potentially possible. The solution is a range gate that has a good "off" state at all frequencies. None of the problems described in this paragraph are particularly difficult to solve, but if they are allowed to occur the system will not function properly.

The results for a low SNR are shown in Figure 17. The target enhancement through this technique is dramatic. The return from each scatterer is at, or slightly below, the noise level. With two scatterers the target is clearly visible and with three scattering centers the target stands out even more. Quantitative measurements of the SNR were difficult to obtain because the noise and signal bandwidths were not necessarily the same. It is clear, however, that the system is capable of significant target enhancement even at very poor signal-to-noise ratios.

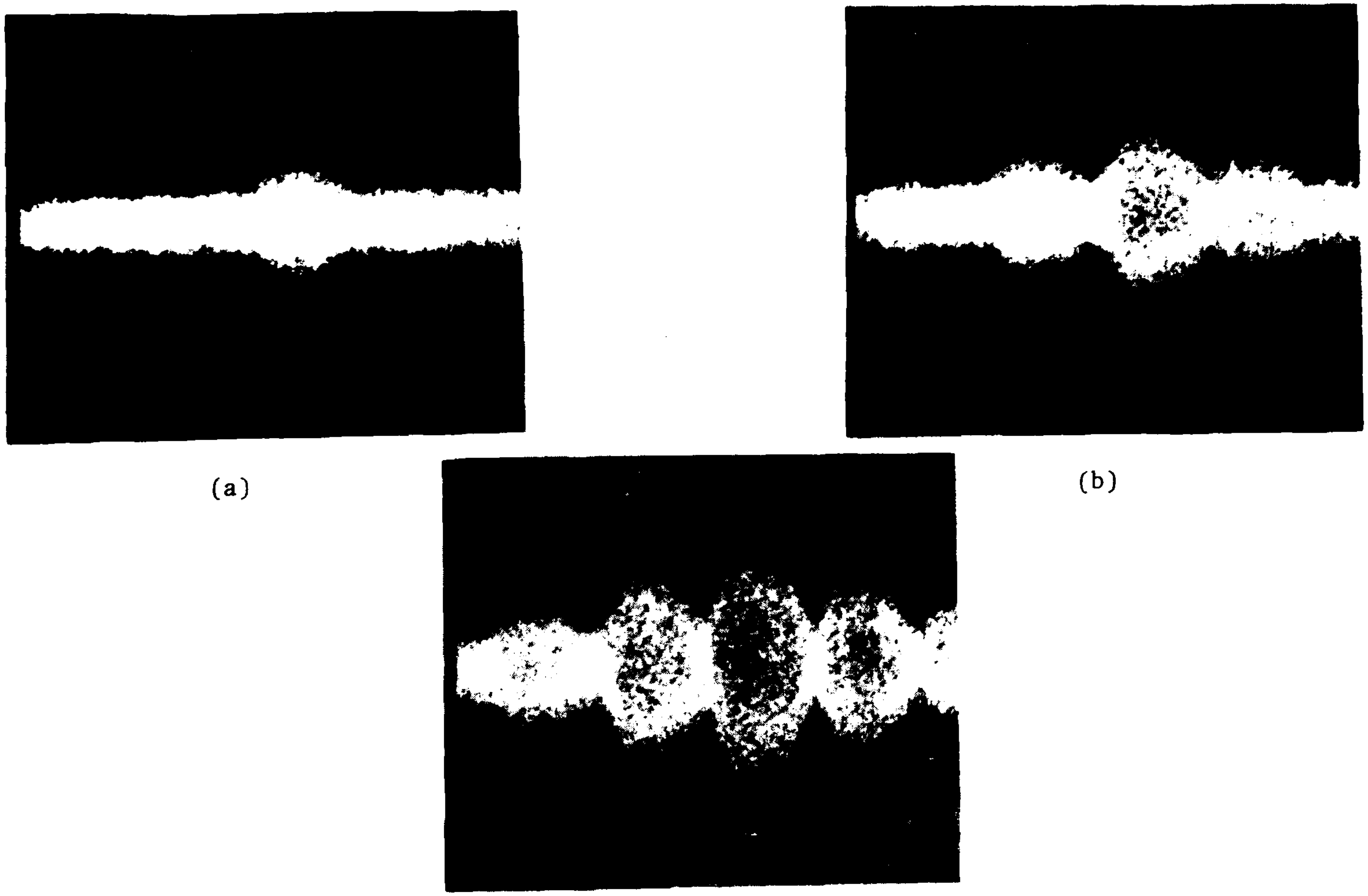
3.3 Dynamic Two-Target Tests

Dynamic tests of the adaptive system were performed using a two scattering center target. The targets were separated by 4.5 feet and were in line at 0° aspect. The pilot pulse (Figure 18) was nominally 8 nsec. wide. The tap spacing and gate width were 4 nsec. providing two samples per pulse width.

Figures 19 through 22 are photographs of the signals present at various times in the system as the target was rotated from 0° aspect to 45° aspect where they become unresolvable. Over this range of aspect angles the relative phases of the two scatterers changed by about 16 cycles.

In Figures 19 through 22 the top picture shows the target return when the pilot pulse is transmitted and the bottom picture shows the target return when the adapted signal is transmitted. From 5° to 30° aspect angle the return with the adapted signal shows very nearly the expected signal enhancement and is virtually constant. At 45° aspect the two scattering centers are not resolvable and the degree of enhancement decreases noticeably.

The enhanced returns shown in Figures 19, 20, and 21 show the signal distortions introduced by finite width sampling with nonrectangular gate pulses. The double-peaked appearance would, of course, not be apparent if the receiver bandwidth were matched to the pilot pulse spectral width.



(a) (b) (c)

FIGURE 17 LOW SNR RESULTS

a) One Scatterer b) Two Scatters c) Three Scatterers

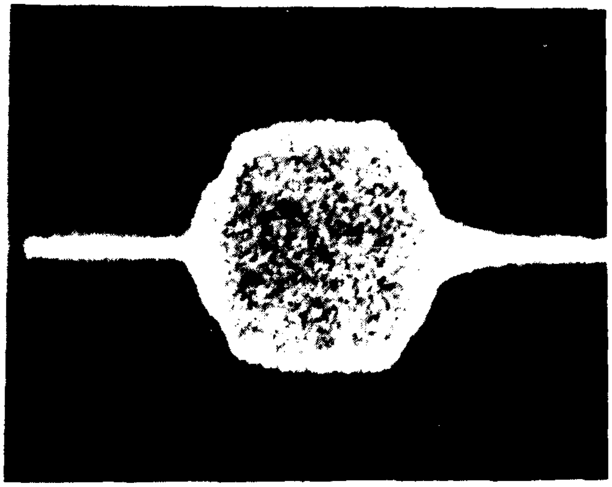
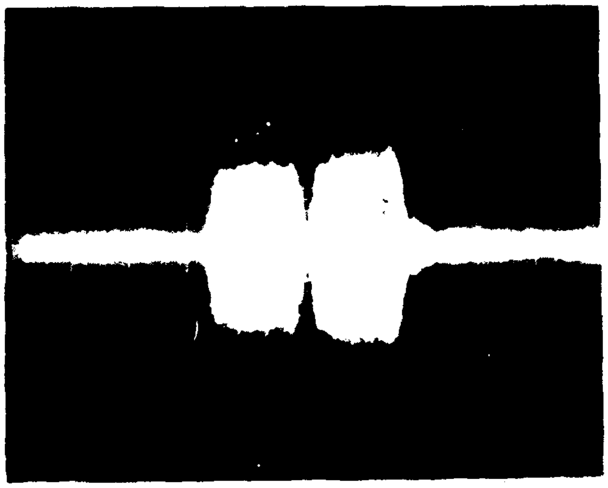
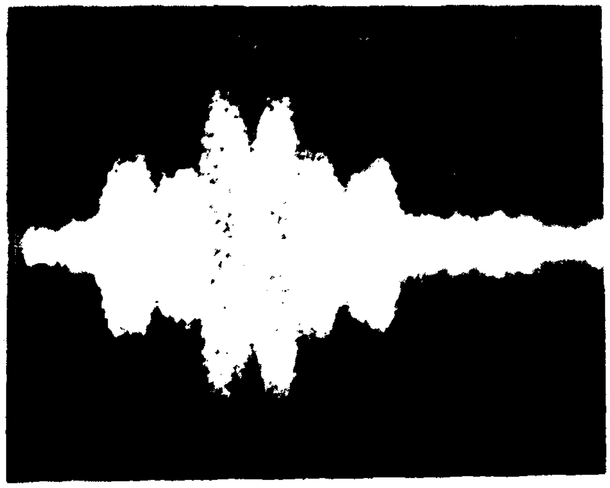


FIGURE 18 PILOT PULSE FOR DYNAMIC TWO-TARGET TESTS

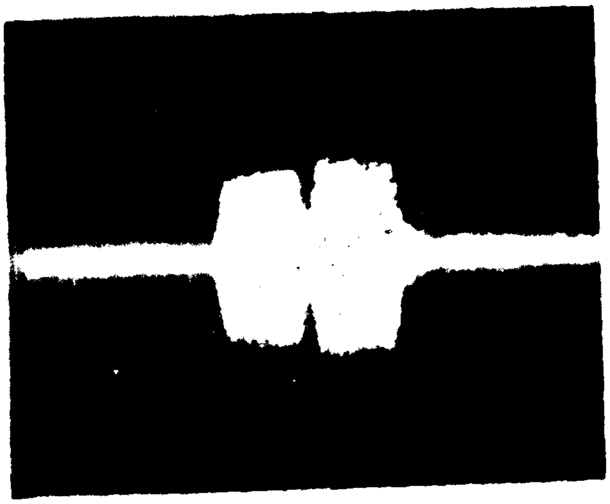


(a)

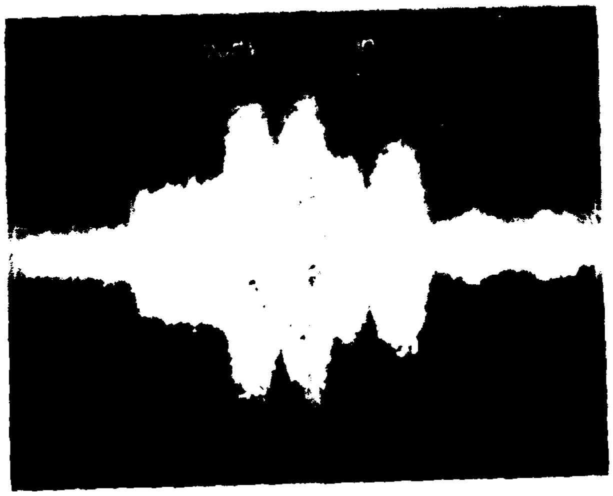


(b)

FIGURE 19 DYNAMIC TWO-TARGET TESTS. 5° ASPECT
a) Response to Pilot Pulse
b) Response to Adapted Signal



(a)



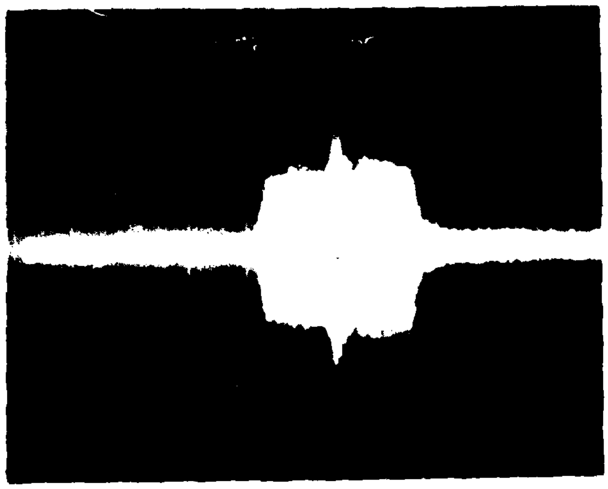
(b)

FIGURE 20 DYNAMIC TWO-TARGET TESTS. 20° ASPECT
a) Response to Pilot Pulse
b) Response to Adapted Signal

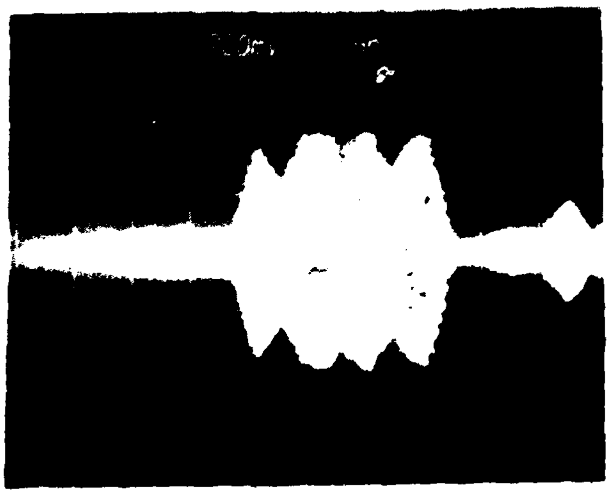
(a)

(b)

FIGURE 21 DYNAMIC TWO-TARGET TESTS. 30° ASPECT
a) Response to Pilot Pulse
b) Response to Adapted Signal



(a)



(b)

FIGURE 22 DYNAMIC TWO-TARGET TESTS. 45° ASPECT
a) Response to Pilot Pulse
b) Response to Adapted Signal

4.0 SWEPT FREQUENCY MEASUREMENTS

An artificial target consisting of 10 point targets was constructed and the long pulse radar return measured as the frequency was stepped from 2.6 to 3.6 GHz in 10 MHz steps. The configuration used was intended to be the same as one of those considered in a theoretical study by Purdue University, entitled "Space Time Signal Processing of Radar Returns" under Contract F30602-75-C-0082.

The nominal configuration is shown in Figure 23 where the dimensions are in meters. The actual configuration is listed in Table I and is a close approximation to the nominal one scaled by a factor of 3.94:1. The Y-dimension given in this table is actually the radar range from the antenna relative to an arbitrary reference and was determined electrically. The X-dimensions were measured physically and are not precise (the radar cross section does not depend upon displacements transverse to the radar line of sight).

The range and amplitude information on the individual targets contained in Table I were determined in the following fashion. The targets, starting with number 1, were individually mounted and positioned by monitoring the phase of the radar return at five frequencies spaced across the measurement band. When the phases agreed with those computed for a target at the nominal range the target position was marked and the target removed. When the location for all targets had been marked in this fashion, all 10 targets were mounted and the radar return (amplitude and phase) was recorded at the 100 frequencies. The targets were then removed one at a time, starting with number 1, and the return from the partial array of targets recorded at the same 100 frequencies. The characteristics (amplitude and radar range) of each target, as it was in the array, was then determined by taking the vector difference between the data from different partial arrays. Thus, the parameters for target 5 were found by taking the difference between the data recorded with targets 5 through 10 and the data recorded with 6 through 10. This procedure was necessary for two reasons. First, it was found to be impossible to remove and reposition a target with sufficient accuracy. Second, because of multiple scattering effects, the phase and amplitude response of a scatterer was different when in the array then when it was alone.

The theoretical response, calculated using the parameters given in Table I, and the measured response are plotted in Figure 24. The agreement is very good.

The original plan was to measure the response at several other aspect angles. As the target array was not a rigid structure this would have been very time consuming. Since the results of theory and experiment agreed so well in

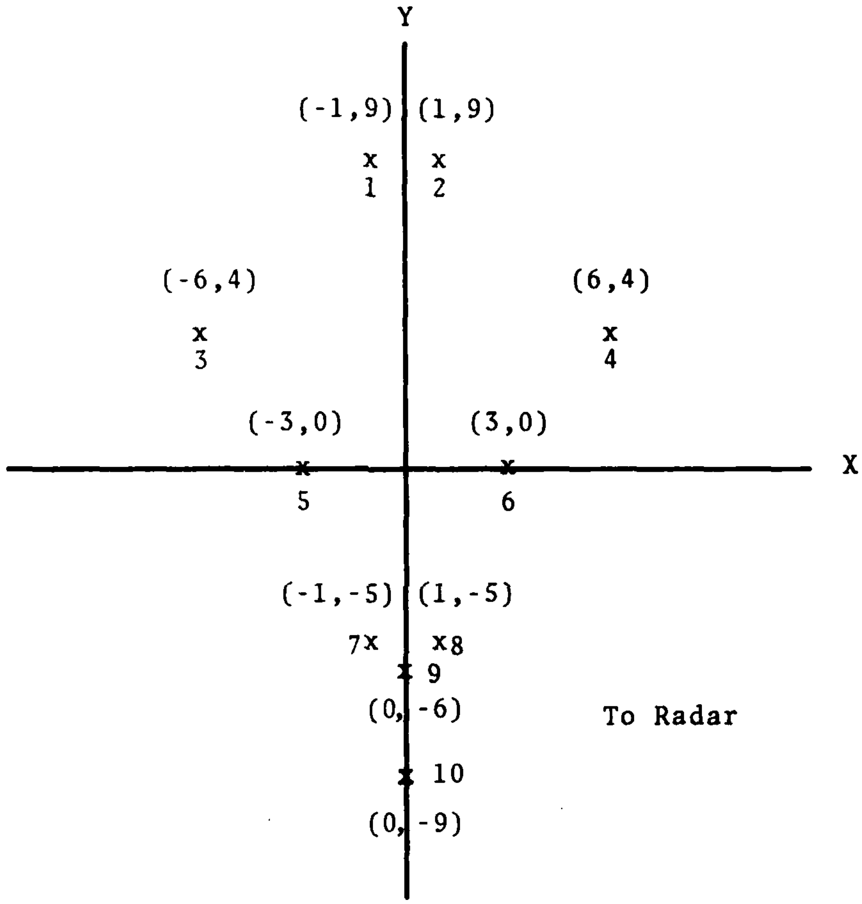


FIGURE 23
NOMINAL TARGET CONFIGURATION FOR
SWEPT FREQUENCY MEASUREMENTS

TABLE I
ACTUAL TARGET PARAMETERS FOR
SWEPT FREQUENCY MEASUREMENTS

Target	X (Inches)	Y (Inches)	Amplitude
1	-10	90.1	0.84
2	10	89.9	0.79
3	-60	39.8	1.00
4	60	40.0	1.26
5	-30	- 0.3	1.00
6	30	- 0.3	1.12
7	-10	-50.0	1.00
8	10	-50.1	0.56
9	0	-60.1	0.79
10	0	-88.00	1.00

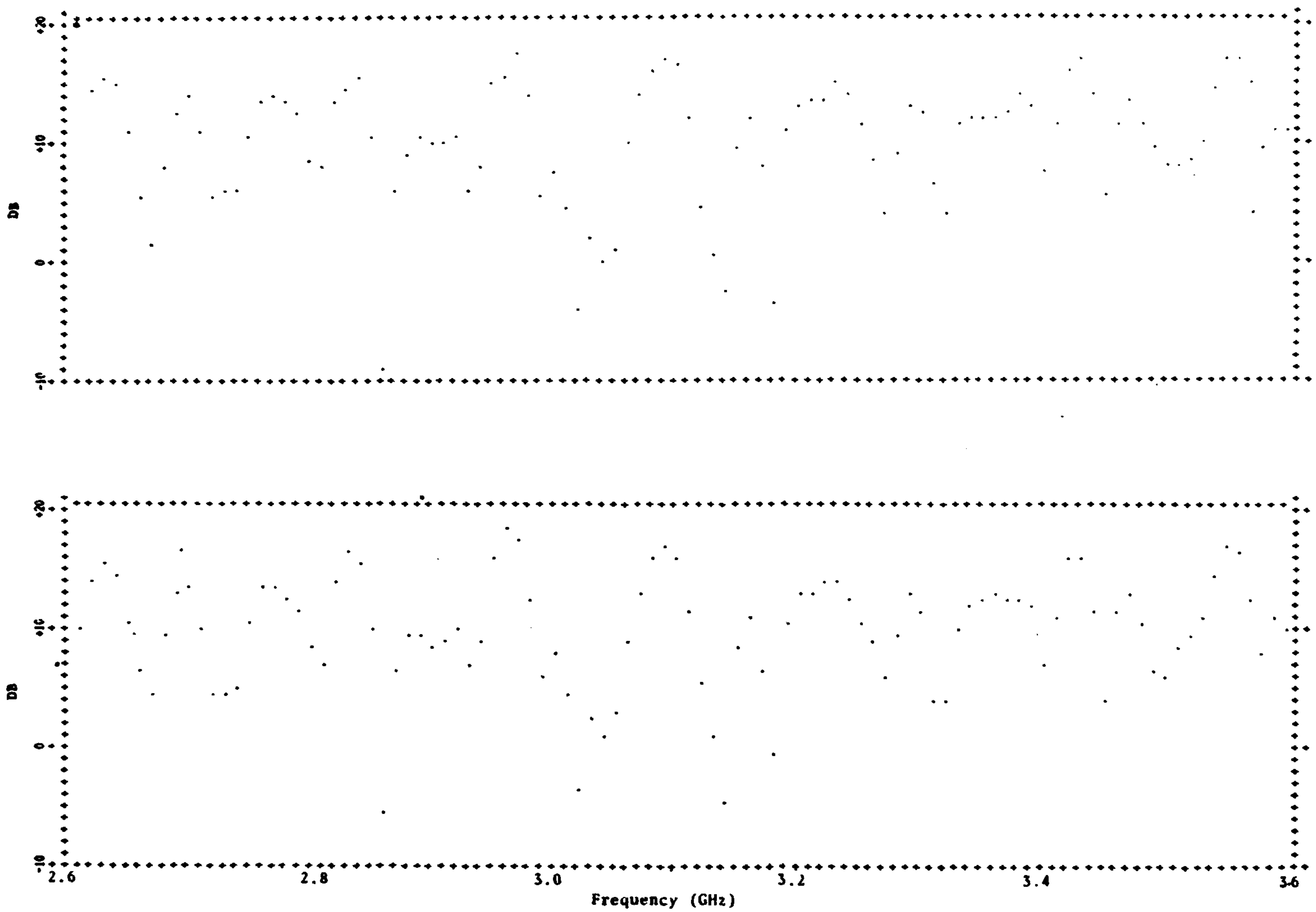


FIGURE 24 STEPPED FREQUENCY RESULTS
a) Measured
b) Computed

the case that was measured it was felt that additional aspect angles would have been more nearly a test of how well targets can be positioned than a test of the ability to compute the response of known targets. Consequently, the additional aspect angle measurements were omitted.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A technique for adaptively generating the transmitting waveform for a time domain approach to the target enhancement problem was demonstrated. The desired transmitter waveform was the time reverse of the impulse response of the target. The technique developed in this program generated a piecewise approximation to the ideal waveform. Measurements utilizing a breadboarded implementation of the technique demonstrated that it is capable of adapting in real time to a dynamically changing target structure. Tests using artifically introduced noise demonstrated that the technique will achieve significant target enhancement even when the returns from the individual scattering centers on the target are at or below the noise level.

A number of problem areas in converting the concept into hardware were found and solutions were devised. Several of these problems were associated with the breadboard nature of the hardware and would not occur with a properly designed and integrated package.

The implementation differed from the one originally proposed in two significant respects. First, it was shown to be necessary to sample the pilot pulse return at intervals of less than one-half the pulse width. All other factors being equal, the smaller the sampling interval the better the results. Above about four samples/pilot pulse width, however, the improvement is slow and the difficulties and cost of implementation increase rapidly. A finished piece of hardware would therefore probably sample at intervals of 2 - 4 samples/pulse.

The second major change in the implementation that was required was the inclusion of a network to conjugate the phases of the components of the pilot pulse response. Inclusion of this network is necessary if the system is to function. It would, however, result in cancellation of any doppler shift of the target return. If no other steps were taken this would result in disabling any part of the radar which depends upon doppler, MTI for example. This problem is not necessarily a trivial one and is inherent in the concept.

The matched-signal concept in the frequency domain was verified by stepped frequency measurements on a 10-scatterer target. The agreement between theory and measurement was quite good when the true electrical positions of the scattering centers were used. Evaluation of an adaptive implementation of the frequency domain approach was not within the scope of this effort.

When considering applications of the matched-signal concept, whether in the time or frequency domain, the purpose should be kept in mind. The idea is to enhance returns from targets which consist of a number of point scatterers. This statement applies to clutter as well as to ships or planes. It is possible that in some circumstances the clutter would be enhanced more than the target resulting in reduced detectability. This problem is closely related to the MTI problem mentioned previously. The technique is certainly promising for situations where noise is the system limitation. It appears to have somewhat less promise where clutter is the major problem. Broadly speaking, the matched signal technique, without a priori knowledge of the target structure, is a viable trade-off for increased transmitter power.

5.2 Recommendations

The feasibility of adaptively transmitting a waveform that is matched to the impulse response of the target has been demonstrated under laboratory conditions. Translating the laboratory breadboard into a piece of hardware capable of operating in a real environment against actual targets will require a considerable amount of study and design effort.

Initially, a design study to examine alternative implementation techniques should be undertaken. This study should compare different function implementation techniques by analysis or by measurements on breadboarded components, whichever is appropriate. An example where such a comparative study is required is whether or not the gating in the time conjugate network should be at RF, at baseband, or via the reference signal used in the phase conjugate network. In principle, all three methods will work. In practice, however, there may well be significant advantages to one of them. This study should identify and evaluate design trade-offs, the relative power in the pilot and adapted signals for example. The desired result of this design study would be a system design complete to the block diagram level but not down to the detailed design level. That is, a stripline coupler might be specified but not designed.

It has been demonstrated that the technique works for modeled targets consisting of a set of discrete scatterers and that real targets can be approximated by such a set. The degree to which the deviation of real target signatures from the model would alter the effectiveness of the technique remains to be evaluated, however. Consequently, an experimental evaluation of the matched signal concept as applied to a real target should be undertaken. This could be either a part of the design study effort or a separate project and could utilize a scaled target model.

A program for detailed design and prototype construction would follow unless significant unsolved problem areas were found in the design study.

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